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ELECTRICAL PERFORMANCE VERIFICATION METHODOLOGY FOR THE P-BAND SAR PAYLOAD OF THE BIOMASS CANDIDATE MISSION

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ABSTRACT

In this paper, an electrical performance verification methodology is proposed for the large deployable reflector antenna of the BIOMASS P-band (435 MHz) synthetic aperture radar (SAR). The proposed methodology is based on measurement of the feed characteristics, such as complex pattern and radiation efficiency, and then calculation of the radiation pattern and gain of the entire SAR antenna with appropriate simulation software. The prototype feed was measured in several configurations with spherical, cylindrical, and planar near-field techniques. The measured results for the feed were then used in calculation of the radiation pattern and gain of the entire reflector antenna. Main emphasis of this work was put on assessment of the achievable pattern and gain uncertainty for the entire antenna and its compliance with the SAR requirements.

1. INTRODUCTION

The BIOMASS candidate mission is currently undergoing its feasibility phase in the selection process for the seventh Earth Explorer programme of the European Space Agency [1]. The main payload of the BIOMASS is a P-band (435 MHz) synthetic aperture radar (SAR) with an antenna aperture of approximately 110 m^2 with full polarimetric and multi-pass interferometric capabilities [2]. The antenna configuration based on a large deployable reflector antenna (LDA) illuminated by a small feed array was selected as a baseline for the second part of the feasibility study.

The deployable mesh reflector has a projected aperture with diameter of 11.5 m and a focal length of 7.5 m. The dual-polarized feed is a 2×2 patch array of about 1 m^2 located atop of the satellite with dimensions of about 1×1.5×3 m^3 (see illustration in Fig. 1). The feed and the reflector are folded towards the satellite during the launch and deployed in orbit.

The required one way gain accuracy for the SAR antenna is set to be better than 0.15 dB (1σ), which represents a very challenging value considering the very low operation frequency and the 12×15 m^2 size of the offset reflector.

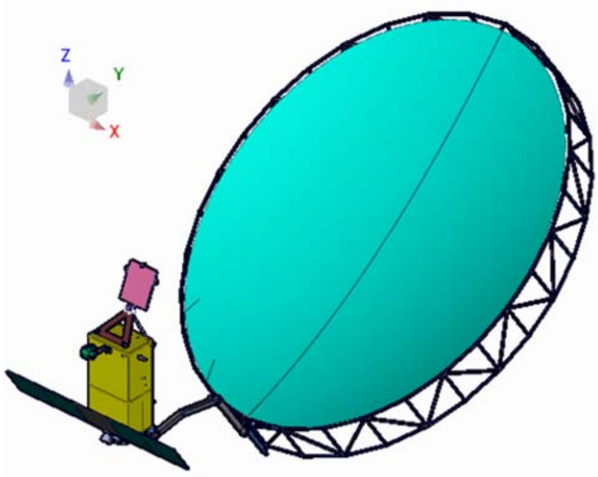

Figure 1. The BIOMASS satellite with the deployable reflector antenna.

2. STUDY OF VERIFICATION APPROACHES

The on-ground electrical performance verification of such antennas is associated with serious technical challenges due to their large physical size, low operation frequency, and mechanical deformations under the gravity force. Possible verification strategies for this large deployable reflector antenna were reviewed and analysed in [3].

The first approach is measurement of the entire SAR antenna. In this approach, the SAR antenna is deployed in an appropriate anechoic chamber and its RF characteristics are measured with e.g. Planar Near-Field (PNF) technique. The advantage of this approach is that the whole antenna is validated in one run in the final deployed configuration. This approach, however, faces a series of practical issues:

- The deployment mechanisms are designed to work in zero-gravity conditions and thus deployment in the gravity force may not be possible. Usual gravity compensation approaches may not be directly applicable to this configuration.
- The gravity force affects the shape of the mesh forming the reflecting surface and the latter thus

does not have the correct shape. Potentially, various gravity compensation approaches can be used to correct the surface shape to be within the required accuracy.

- The RF measurement of the deployed reflector of the considered size with the satellite, which is about 12m×18m×10m in an upwards looking orientation, requires a shielded anechoic chamber of about twice larger size in each dimension operating at 435 MHz.
- The RF measurement of the deployed reflector with a PNF technique would require the scan zone area of about 20m×30m for the 45° valid angular region.

In view of the listed practical issues, the measurement of the entire reflector is considered as extremely technically challenging and thus not feasible.

The second approach is measurement of a scaled model. In this approach, a down-scaled model of the reflector antenna and the satellite are manufactured and measurements are performed at the correspondingly up-scaled frequencies. However, the following disadvantages of this approach must be noted:

- Not the actual reflector antenna, but another (scaled) antenna is characterized. The obtained characteristics provide the knowledge about the antenna concept and geometry, but not the actual antenna.
- Not all properties and characteristics can be scaled, e.g. conductivity and dielectric permittivity of the materials, or some physical dimensions, e.g. thin films, coatings, etc.
- Manufacturing an exact scaled model of the feed array may represent a significant challenge, since even small deviations in the physical dimensions and/or electrical properties of the materials may result in unacceptable difference in RF characteristics.

In view of the above disadvantages, the measurement of the scaled model of the SAR antenna is considered as extremely technically challenging as well as not providing all necessary information and thus not satisfying the test requirements.

The third approach is measurement of the feed array followed by calculation of the secondary pattern. In this approach, the feed array is characterized separately by measurements, while the pattern and gain of the entire SAR antenna are calculated by a suitable electromagnetic modeling tool. This approach has been validated on a number of satellite reflector antennas, both commercial and scientific, such as Planck [4]. This approach was found to be the most promising one for the P-band SAR payload, and it was investigated further, both by simulations and by measurements.

This approach has several advantages and disadvantages. The main advantage is, clearly, that the verification measurements are to be done on a much smaller antenna under test, the feed array, which can be accurately characterized by an appropriate measurement technique. Another advantage is that the reflector has the electrical size of about 17 wavelengths, which allows it to be accurately simulated with the Method of Moments approach, including also the satellite, if proven necessary.

The main disadvantage is that the number of uncertainty factors to be taken into account increases substantially, and the final uncertainty budget must include rather many additional terms, each of which must be carefully estimated; see below. Another disadvantage is that the reflector shape and electrical properties must be accurately known for its proper modeling.

3. UNCERTAINTY BUDGET

The total uncertainty budget for the selected validation approach consists of the following terms:

1. Measurement uncertainty of the feed
2. Multiple interactions between the reflector and satellite
3. Influence of the reflector support arm
4. Uncertainty of the field incident on the reflector, depending on the feed model used in the measurements
5. Uncertainty of the reflector surface modeling
6. Uncertainty of the simulation method
7. Uncertainty related to deployment accuracy and repeatability

Item 2 comes into consideration, since it is highly preferable to avoid modeling the entire satellite, and just consider scattering of the field radiated from the feed, represented in terms of spherical wave expansion, from the reflector alone. In item 3, for similar reasons, the scattering from the support arm is neglected.

For item 4, several feed configurations were considered: 1) feed array alone; 2) feed array with its support structure and the top plate of the satellite; and 3) feed array with the entire satellite. Clearly, Configuration 1 is the simplest from the viewpoint of measurements, but it provides the worst feed model, since e.g. scattering from the feed support structure and from the satellite are not taken into account. Contrary, Configuration 3 is the most accurate in terms of the feed modeling, but it is also the most challenging for obtaining accurate measurement results due to much larger overall size of the object under test. The considered feed Configurations 1, 2, and 3 are illustrated in Fig. 2.

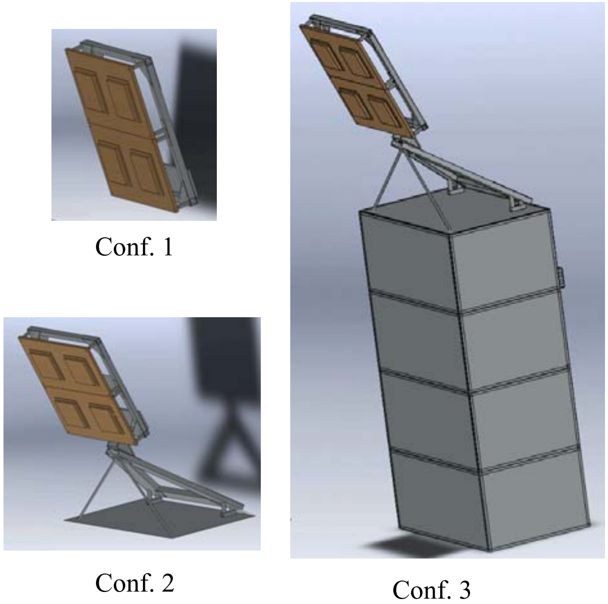

Figure 2. Feed configurations considered in this study.

In item 5, the difference of the final surface shape from the assumed one is taken into account, including both the available knowledge of the physical surface properties and shape, and its representation in the simulation tool.

The uncertainty mentioned in item 7 is not directly related to the verification methodology, but it must be included, since it represents an additional uncertainty source with direct influence on the SAR pattern uncertainty.

Investigations for the items 2-7 in the budget were carried out by simulations [3]. For the items 1 and 4, some representative measurement data and typical uncertainties at 435 MHz were obtained from two measurement campaigns carried out with the prototype feed array [5] and representative satellite model [6].

4. SIMULATIONS

The feed system is located on top of rather large conductive satellite scattering the field, which may have a strong influence on the feed radiation pattern. The first task is then to determine, if this scattering is significant, and thus the satellite, or part of it, must be included when measuring the feed characteristics for achieving the necessary accuracy for the entire antenna pattern. The radiation pattern from the complete antenna including the feed system, the feed support structure, the satellite body and the reflector was calculated with the GRASP software [7] based on the Method of Moments (MoM) approach. This result is then used as a reference in the following comparisons.

The feed measurements are simulated by calculating the pattern from the feed as if it was measured in a radio anechoic chamber. Several measurement configurations are considered: the feed alone; the feed with its support structure and the top plate of the satellite; and the feed with the entire satellite (see Fig. 2). The simulated pattern is then represented in terms of spherical wave expansion.

A simplified problem is then considered, where only the incident field represented by the spherical wave expansion is used to illuminate the reflector and the secondary field is calculated and compared to the reference solution. In this simplified problem, the multiple scattering between the reflector and the feed, consisting in Conf. 3 of the feed array, its support structure, and the entire satellite, are not taken into account (item 2 in the uncertainty budget). In a similar way, the simulation was carried out with and without presence of the reflector support arm (item 3 in the budget). Removing consecutively the satellite and the feed support structure, different feed configurations were simulated (item 4 in the budget). Uncertainties related to the deployment accuracy and repeatability and the reflector surface errors were simulated introducing expected deviations in the reflector position and orientation and the reflector shape (items 5 and 7 in the budget).

In this way, the uncertainty of the secondary antenna pattern for all respective items in the budget was evaluated and compared against the requirements.

5. MEASUREMENT CAMPAIGNS

In order to obtain realistic measurement uncertainty estimates and investigate possible problems related to characterization of the feed at P-band, two measurement campaigns were carried out. The first campaign included measurements of the prototype feed array in all considered configurations, 1, 2, and 3, at the DTU-ESA Spherical Near-Field (SNF) Antenna Test Facility at the Technical University of Denmark. The measurement of the feed array on top of the BIOMASS satellite model (Conf. 3) at the DTU-ESA Facility is shown in Fig. 3.

The second campaign included measurements of the feed array in configurations 1 and 2 at the Near-Field facility of the Naval Maintenance Establishment (NME) in Den Helder, the Netherlands, with Planar and Cylindrical Near-Field techniques. The measurement of the feed array (Conf. 1) at the NME Facility is shown in Fig. 4.

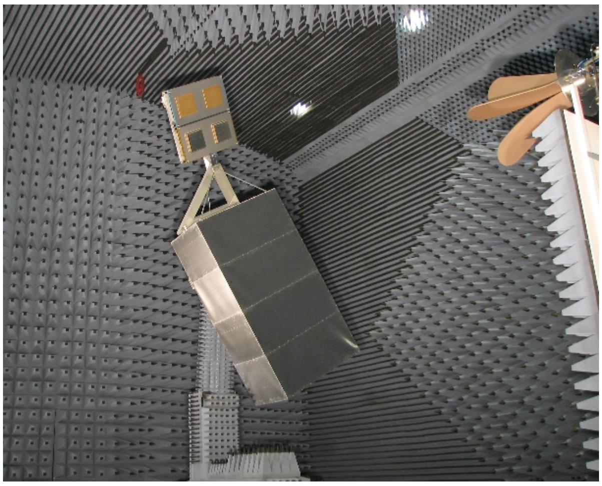

Figure 3. Measurement of the feed array on top of the BIOMASS satellite model (Conf. 3) at the DTU-ESA Facility.

In each campaign, special attention was given to investigations of measurement uncertainty. In particular, the uncertainty items known to give the largest contributions at these low frequencies were investigated by additional measurements: multiple reflections between the Antenna Under Test (AUT) and probe; scattering from the chamber walls; and scattering from the AUT tower. In addition, the effect of the measurement support frame interfacing the AUT and the antenna tower mounting flange was investigated [6].

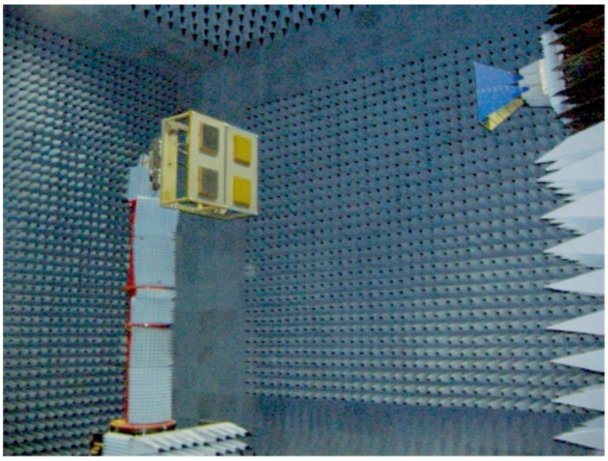

Figure 4. Measurement of the feed array (Conf. 1) at the Naval Maintenance Establishment.

Comparison of the measurement results from the campaigns have shown that the SNF technique provided the results with the smallest uncertainty as well as the full-sphere coverage for the measured data, and this technique was recommended for the on-ground performance verification of the feed array. Several recommendations were also given regarding improvements of the test procedures in order to reduce critical uncertainty sources in the gain measurement.

6. SIMULATIONS USING THE MEASURED FEED DATA

The measurement campaigns have provided valuable data with realistic uncertainties for all considered feed configurations. Several additional measurements carried out for uncertainty investigation allowed separating the individual uncertainties and creating additional results with and without these uncertainties.

The measurement data were then used in calculation of the secondary pattern. Comparing the secondary patterns calculated with different input measurement data (i.e. with and without particular uncertainty) provided estimates for the so-called propagation coefficients for those uncertainties into the secondary pattern. These propagation coefficients quantify the influence of particular feed measurement uncertainty sources on the secondary pattern. A coefficient less than 1 means that the uncertainty source has less influence on the secondary pattern than on the feed pattern.

It was found that most of the measurement uncertainties have propagation coefficients significantly less than 1. On the other hand, it was found that the effect of the measurement support frame, interfacing the feed and the antenna tower, has propagation coefficient close to 1.

It is noted that the effect of the measurement support frame was found to be the largest term in the feed uncertainty budget, exceeding the other terms by a factor of two. This large effect is explained by several factors: non-optimum design of the frame; its proximity to the edges of the feed array carrying rather strong diffraction currents; as well as possible scattering of the back radiated fields. As an outcome, recommendations were given regarding development of a special design of this support frame and modification of the feed array design, if possible, to decrease its back radiation, thus ensuring their minimum interference during the on-ground performance verification.

7. ANALYSIS OF THE RESULTS

Summarizing the results of all the investigations, the following conclusions have been reached:

- Interactions between the reflector and the satellite with the feed are negligible;
- Influence of the reflector support arm is negligible;
- The calculation uncertainty of the employed numerical tool, GRASP software based on the MoM approach, is negligible. Application of the combined PO/PTD approach was also investigated and found possible;
- Sensitivity analysis regarding relative pointing and displacement of the feed and reflector has

concluded that all displacement and pointing uncertainties that keep the beam maximum within 0.05° from the nominal direction will not affect the pattern shape, only the pointing direction;

- Sensitivity analysis regarding reflector surface shape has concluded that for a typical value of 5 mm RMS for the reflector surface uncertainty, it is recommended to keep the correlation distance below 2.5 m;
- The analysis of the simulation results for the three feed configurations has concluded that Conf. 1 does not provide enough accuracy to meet the pattern uncertainty and pointing requirements, while both Conf. 2 and Conf. 3 provide sufficient accuracy of the incident field;
- The analysis of the measurement uncertainties for the three feed configurations have shown that Conf. 3 does not meet the secondary pattern uncertainty requirements, while both Conf. 1 and Conf. 2 have acceptably low uncertainty.

Summarizing the above conclusions, the most promising approach consists of measurement of the radiation characteristics of the feed with its support structure and the satellite top plate (Conf. 2) with the SNF technique, followed by calculation of the pattern and gain of the entire SAR antenna by the MoM computational tool of GRASP or similar accurate simulation software.

In the proposed performance validation methodology, the gain of the SAR antenna is represented by a product of the directivity and the radiation efficiency, where the latter consists of two contributions: measured feed radiation efficiency and calculated reflector radiation efficiency. The feed radiation efficiency is determined from the SNF measurements by comparing the total radiated power of the feed and that of the standard gain horn (SGH) antenna. Thus, the total uncertainty budget of the SAR gain consists of several terms with the largest contributions from the reflector antenna peak directivity uncertainty, feed total radiated power, and SGH uncertainty.

The final uncertainty budgets for the secondary pattern directivity and gain compiled using the results of the above simulations and the available measurements are shown in Table 1 and Table 2, respectively. It is noted that the obtained estimate for the gain is close, but slightly exceeding the specified requirement. Several improvements of the measurement procedures have to be implemented in order to decrease the largest terms in the gain uncertainty budget mentioned above.

Table 1: Uncertainty budget for the peak directivity.

Uncertainty item	Std. dev. σ, dB
1. Feed measurement uncertainty (neglecting measurement support frame)	0.03
2. Reflector-spacecraft interactions	0.01
3. Reflector support arm influence	0.01
4. Secondary pattern calculation (Conf. 2)	0.04
5. Deployment accuracy	0.03
6. Reflector surface modeling	0.04
7. Numerical tool	0.01
Root Sum Square:	0.07

Table 2: Uncertainty budget for the peak gain.

Uncertainty item	Std. dev. σ, dB
1. SAR antenna peak directivity	0.07
2. Feed total radiated power	0.09
3. SGH radiation efficiency	0.10
4. Feed mismatch correction	0.01
5. SGH mismatch correction	0.01
6. Signal source mismatch	0.04
7. Drift	0.03
8. Cable variations	0.02
9. Reflector radiation efficiency*	-
Root Sum Square:	0.16

* The calculation uncertainty of the reflector mesh radiation efficiency is assumed to be negligibly small in view of negligibly small conductivity loss of the reflector mesh at 435 MHz.

8. PROPOSED PERFORMANCE VERIFICATION METHODOLOGY – STEP BY STEP

The proposed performance verification methodology for the P-band SAR payload for the BIOMASS candidate mission is the following:

Measurements:

1. The S-parameters of the feed in Conf. 2 are measured;
2. The full-sphere complex relative pattern of the feed in Conf. 2 is measured with the SNF technique;
3. The radiation efficiency of the feed in Conf. 2 is measured using the substitution technique with a calibrated gain standard;

4. Measurements for establishing uncertainty budgets for the radiation pattern and efficiency are carried out;
5. Post-processing of the measured data is carried out, including transformation from the measurement to the feed coordinate system, conversion to the necessary time convention, normalization, and data format;

Simulations:

6. The spherical wave expansion (SWE) of the feed is calculated;
7. The reflector model is established and the scattered field from the feed SWE is calculated. Radiation efficiency of the reflector is calculated;
8. Total secondary field is calculated from the sum of the incident and scattered fields. Directivity of the secondary pattern is calculated;
9. Gain is calculated by a product of the secondary pattern directivity, feed radiation efficiency, and reflector radiation efficiency;
10. Transformation to the necessary output coordinate system, conversion to the necessary time convention, normalization, and data format;
11. Calculations for establishing uncertainty budgets for the radiation pattern and gain are carried out.

Further details of the proposed methodology can be found in [3].

An independent in-orbit validation of the pattern characteristics, checking also for geometrical and deployment errors beyond the accuracies assumed for the uncertainty budget, will finally be made as part of the commissioning and operational phase of the mission. The expected outcome is that the independent in-orbit validation confirms the knowledge of the pattern characteristics obtained from the on-ground performance verification.

9. CONCLUSIONS

An optimum on-ground electrical performance verification methodology is proposed for the BIOMASS P-band SAR antenna. The methodology is based on measurement of the feed characteristics, such as complex pattern and radiation efficiency, and then calculation of the radiation pattern and gain of the entire SAR antenna with appropriate simulation software.

Compliance analysis of the derived uncertainty budgets for the main parameters of the P-band SAR payload was carried out and recommendations on improvement of the test procedures to reduce critical uncertainty sources were provided. In particular, it was found critical to develop a suitable design of the measurement support frame for the feed, which introduces minimum disturbance into the measured feed pattern. Modification of the feed array design, if possible, to decrease its back radiation, is also desirable, thus ensuring minimum interference between the feed and the measurement support frame during the on-ground performance verification.

It is concluded that the proposed performance verification methodology for the P-band SAR payload allows achieving the specified requirements for all characteristics. Independent in-orbit validation during the commissioning and operational phase of the mission shall be used to confirm the pattern characteristics obtained from the on-ground performance verification.

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